# SEISMIC LOCATION CALIBRATION FOR 30 INTERNATIONAL MONITORING SYSTEM STATIONS IN EASTERN ASIA

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**ABSTRACT**

We review the progress of a collaborative academic-industry research consortium, comprised of five institutions, that has started an integrated series of projects to improve the capability to locate seismic events based on data acquired by International Monitoring System (IMS) stations in Eastern Asia. This effort is to develop and deliver validated high-resolution travel time grids for operational use.

During the first year of work we have focussed on IMS stations in Central Asia and Northern Pakistan, specifically the stations MAK, BRVK, KURK, AAK, AKTO, ZAL, PRPK/NIL, for which we are obtaining preliminary Source Specific Station Corrections (SSSCs). Each station presents its special problems and opportunities. Thus, although only two of these stations (ZAL and NIL) are currently contributing data to the International Data Centre (IDC), we have broadband high-quality data from surrogate stations at or close to the planned IMS sites for the other five sites. In joint projects with the National Nuclear Centre of the Republic of Kazakhstan (NNCRK) and the Institute of Dynamics of the Geosphere of the Russian Academy of Sciences, regional waveforms from Borovoye (BRVK) have become available for 80 Soviet PNEs, 228 Semipalatinsk explosions and 11 Lop Nor explosions. In a joint project with the NNCRK and the Complex Seismological Expedition based in Talgar, Kazakhstan, regional waveforms from 37 Soviet Peaceful Nuclear Explosions (PNEs) have become available for several other stations in Central Asia. Since 1994 we have operated broadband instrumentation jointly with the NNCRK at MAK, BRVK, KURK, and AKTO — enabling, for example, the recording of regional waves from numerous earthquakes throughout Central Asia, and some nuclear explosions (Lop Nor). We have obtained empirical travel times from all these datasets, using published high-quality ground truth information for the Soviet PNEs.

Other valuable sources of empirical travel time information have been the Deep Seismic Sounding (DSS) profiles carried out with chemical explosions in and near Kazakhstan, and DSS profiles carried out with nuclear explosions in the northern part of the former Soviet Union. We have been able to document the variability of regional travel times with these data, finding in particular that *Sn* and *Lg* waves show significant variability. Preliminary Source Specific Station Corrections have been used for stations MAK, AAK, KURK, ZAL, TLY, ULN, NIL, and BRVK to relocate nuclear explosions at Lop Nor, showing improved accuracy and reduced confidence ellipses. We are extending this process of validation to include PNEs and other underground nuclear explosions in the former Soviet Union, and earthquakes for which we have adequate ground truth.

We are on collecting high-precision hypocenter locations for mainland China by applying a double-difference (DD) earthquake relocation technique to travel time data given in the Annual Bulletin of Chinese Earthquakes (ABCE). In areas with dense seismicity, where the DD technique minimizes model effects without the use of station corrections, we find the relocated events cluster in space and appear to delineate local tectonic features. Analysis of the residuals indicates that the phase picks are of high quality, and that they are best suited to image seismicity with high resolution on a local (several km) scale. Increasing earthquake density by including ABCE data from additional time periods might help to relocate earthquakes over larger distances, such as entire fault systems. Such studies have the potential to increase groundtruth data as well as contribute to a better understanding of the tectonic processes in China.

**KEY WORDS**: earthquake location, Peaceful Nuclear Explosions, Chinese seismicity.

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## OBJECTIVE

The goal of this project is to improve the accuracy of estimates of the location of seismic events and to reduce the uncertainty of such estimates on the basis of an interpretation of the arrival times of regional seismic waves observed at 30 stations of the International Monitoring System located in Eastern Asia.

## RESEARCH ACCOMPLISHED

### Introduction

Following the recommendations of two IMS Location Calibration Workshops held in Oslo, Norway, in 1999 and 2000, our approach is to generate station-specific travel times for each observable seismic phase, as a function of distance and azimuth (and depth, where possible). In practice, such travel times are characterized by Source Specific Station Corrections (SSSCs) to the IASP91 travel times. SSSCs are obtained on the basis of (i) early studies based mainly on earthquake data (e.g. Nersesov and Rautian, 1964), (ii) Deep Seismic Sounding, and (iii) recent studies of nuclear and chemical explosions. We are also using (iv) an empirical approach in which phases are picked at IMS stations (or at surrogate stations near IMS sites that are currently not operating), for so-called reference events whose locations are known quite accurately (to within 5 km GT5 quality) on the basis of data obtained from local and regional networks.

Our project began in March 2000. It is a three-year collaborative academic-industry research project led by Lamont and involving a consortium of five institutions. Details of our work are described in Richards et al. (2000) and at http://www.LDEO.columbia.edu/~richards/consortium.html including the list of 30 stations we are studying, their locations, relevant maps, and description of pertinent datasets. During the first year of work we have focussed on the derivation of SSSCs for seven IMS stations in and near Central Asia. Much of our progress to date has been based on major datasets of waveforms and phase picks for 70 Soviet-era Peaceful Nuclear Explosions (PNEs).

We have obtained preliminary SSSCs using the method of Bond r (1999) applied to a model of eastern Asia composed of 20 different regions within each of which we have defined a set of regional travel times. We find that these SSSCs reduce residuals for the phase picks of numerous PNEs. Use of kriging plus SSSCs further reduces residuals. Validation of a set of SSSCs is best done by demonstrating location improvement, and we have begun this phase of our work with relocation of underground nuclear explosions at the Lop Nor test site in China.

Though we have obtained locations of tens of thousands of seismic events in Eastern Asia, estimated on the basis of regional seismic signals recorded by local and regional networks, it is a time-consuming process to identify and document the subset of these events that can with confidence be categorized as GT5 or better. We are engaged in that process, and are developing sets of reference events for several sub-regions of Eastern Asia. Some of these are in China, where it is proving important to locate numerous earthquakes at once, using modern methods to reduce model error that are insensitive to errors in station location.

### First SSSCs

Our first procedure for obtaining SSSCs has used the method described by Bond r (1999), in which our whole study region (Eastern Asia) is first divided into sub-regions within each of which we use available information to obtain travel times as a function of distance for each of the main regional seismic phases (*Pg*, *Pn*, *Sn*, *Lg*). A preliminary regionalization of this type is shown in Figure 1. An assumption underlying Bond r s approach is that structure does not vary laterally within each sub-region. Since travel time (and hence structure) is established for each sub-region, it is conceptually possible to compute the travel time for a path from each point in Figure 1, to each of the 30 IMS stations we seek to calibrate. The correct way to obtain such a travel time, for a path that crosses one or more region boundaries, is to integrate along the actual ray path which in general will be laterally refracted at a region boundary so that the path does not stay in the same vertical plane. However, Bond r (1999) has suggested the following simple formula for obtaining an approximate travel time to distance $X$:

$$T(X) = \text{sum of } [(x_i / X) \,.\, T_i(X)] \qquad (1)$$

where the index $i$ ranges over all sub-regions crossed by the ray path, and $x_i$ and $T_i$ ($X$) are the path length and travel time (for the full distance $X$) in the $i$-th sub-region. The desired travel time is thus obtained as a weighted average of the travel time in each sub-region, the weights being ($x_i$ / $X$), which for each $i$ is just the fraction of the total path lying in sub-region $i$. (A problem with this formula, is that it may be inaccurate for paths of more than 1000 km or more, in application to sub-regions smaller than 1000 km across. An artificial relation between $T_i$ and $X$ is then needed artificial, because the path length here is too long to be fully contained within the sub-region.) Once $T(X)$ is obtained, the source specific station correction (SSSC) is given by

$$T_{SSSC} = T(X) - T_{IASP91}$$

To obtain the regionalization and travel times for each block, in the case of Central Asia, we note first the classic study of Nersesov and Rautian (1964), describing the early work on a big profile carried out by the Complex Seismological Expedition. Khalturin et al. (2001) used observations of small-magnitude underground nuclear explosions at the Semipalatinsk Test Site, and earthquakes with good locations, to obtain a version of the Nersesov and Rautian travel times which is adapted to this test site and surrounding areas. They located several small magnitude events on the test site with accuracy about 5 km using only a few stations. Their results were confirmed by comparison with ground truth information, obtained after the seismically-based locations had been estimated. In addition we have data from 27 Deep Seismic Sounding (DSS) profiles in Central Asia, obtained from Antonenko (1984), Shatsilov (1993), Zunnunov (1985) and the book Seismic Models of the Lithosphere of the main Geostructures in territory of the USSR (1980).

The regionalization indicated in Figure 1 is based on DSS profiles throughout the former Soviet Union, together with many regional studies of China and the Indian sub-continent. Our regionalization is frequently under review within the Lamont consortium. The version we are currently using is described at http://www.LDEO.columbia.edu/~armb.

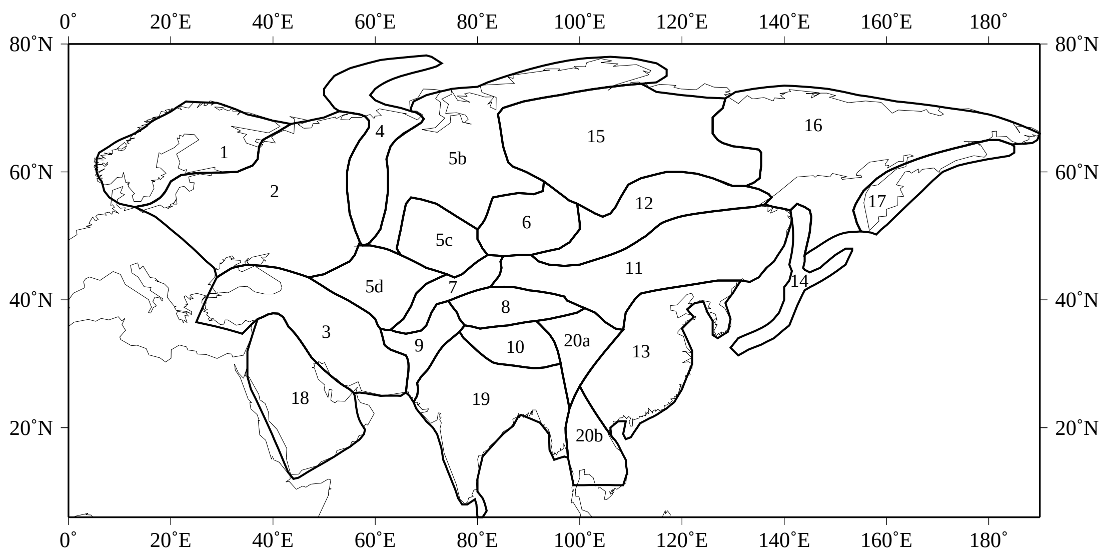


Figure 1. This map shows our preliminary regionalization of most of Eurasia, for purposes of obtaining approximate travel times of regional seismic waves to IMS station in Eastern Asia. For each regional seismic wave of interest (*Pg*, *Pn*, *Sn*, *Lg*), the relationship between travel time and distance is assumed to apply throughout each sub-region.

PNE Records from Borovoye & Talgar Archives

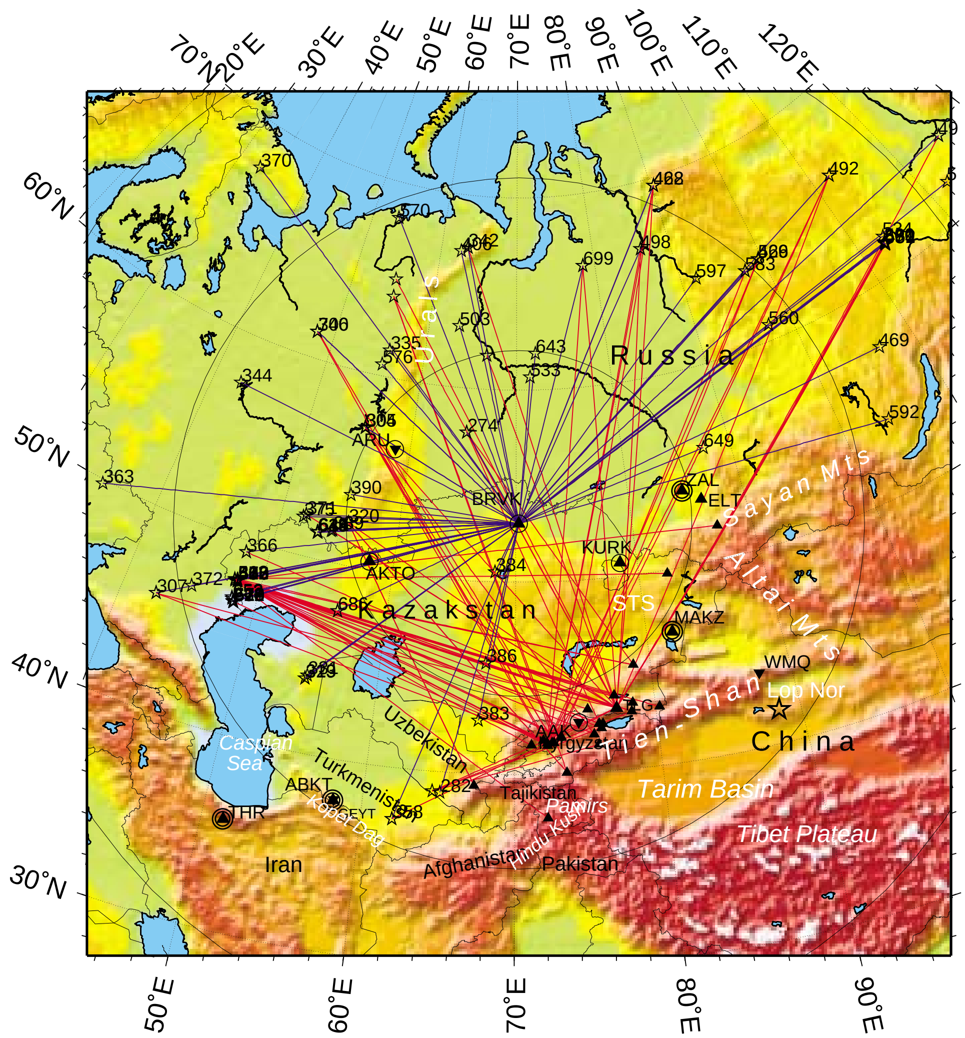


Figure 2. Waveform data from Soviet PNEs (stars) recorded at Borovoye, northern Kazakhstan, and at 26 stations of the Talgar Complex Seismological Expedition, Russian Academy of Sciences, during 1966 to 1988. Paths between 80 PNE sources and Borovoye are indicated by blue lines, while paths of 37 PNEs to Talgar CSE stations are indicated by red lines. Event numbers (Mikhailov et al., 1996) are indicated for each explosion. IMS primary (double circle), auxiliary (single circle), IRIS/GSN (inverted triangle) and Talgar CSE stations (solid triangle) are indicated. Circles centered on BRVK have 1000 and 2000 km radii.

**An evaluation of the SSSC for Borovoye (BRV)**

The IMS includes an auxiliary station at Borovoye, in northern Kazakhstan. Though not yet operating as an IMS station with data flowing to the Vienna IDC, there has been an Observatory at Borovoye acquiring digital seismic data since 1966. In joint projects between the Lamont-Doherty Earth Observatory, the National Nuclear Centre of the Republic of Kazakhstan (NNCRK), and the Institute of Dynamics of the Geosphere of the Russian Academy of Sciences, regional waveforms from Borovoye (BRVK) became

available early in 2001 for 80 Soviet PNEs, 228 Semipalatinsk explosions and 11 Lop Nor explosions. These data are now available to interested users who may obtain the Borovoye waveforms from the Center for Monitoring Research, and the IRIS Consortium (for further information, see http://www.LDEO.columbia.edu/Monitoring/Data/brv_web/brv_archive_web.html). These waveforms are of course useful for a wide variety of research projects, in particular for evaluating the SSSCs obtained from regionalizations such as that of Figure 1 (and associated travel times for each sub-region).

We picked the arrivals of *P*- and *S*-waves from the Borovoye digital waveforms for 70 PNEs, and made use of the GT1 or better information contained in Sultanov et al. (1999) to obtain empirical travel times at BRV for these events. Figure 2 shows the Borovoye (BRVK) location and Soviet PNEs for which we have picked empirical travel times, and also the location of 26 stations of the Complex Seismological Expedition, based in Talgar, Kazakhstan, for which we have additional empirical data based on digitized waveforms from the same events. Figure 3 shows the residuals for these travel times against the predictions of IASP91, and Figure 4 shows the residuals against IASP91 after the preliminary SSSC for BRV has been applied. We have also carried out a series of kriging exercises, using some of the PNE travel times to BRV for this purpose, and the remaining PNE travel times to Borovoye for an evaluation shown in Table 1.

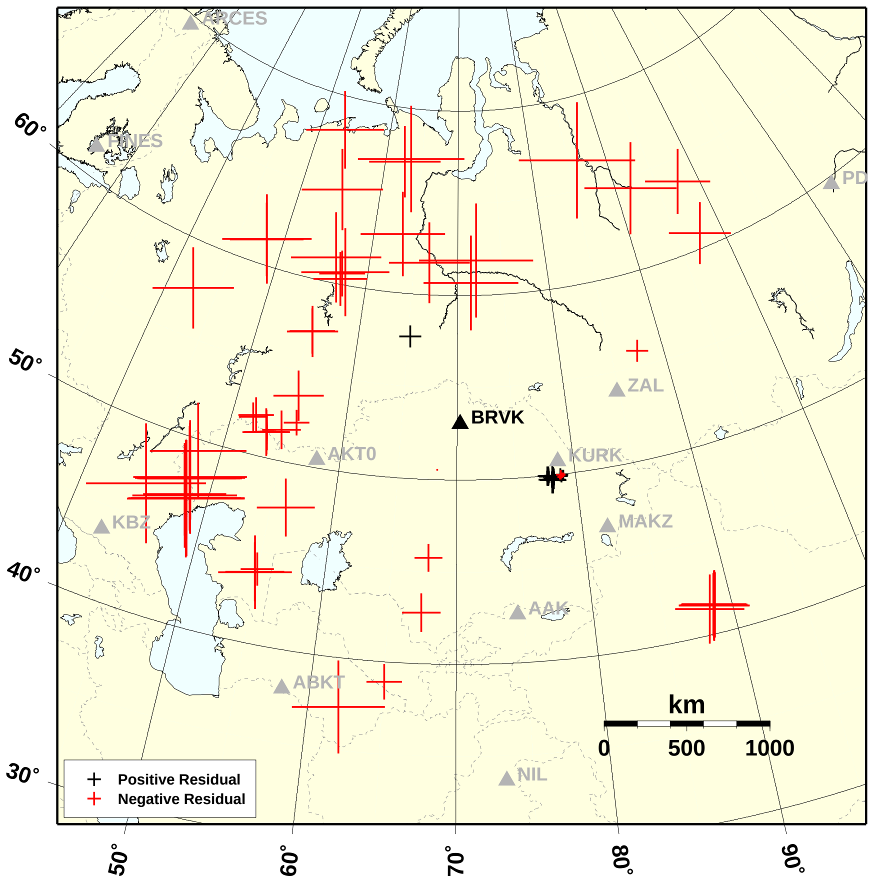


Figure 3. Map of PNE locations for events whose travel time to Borovoye (BRV) has been measured from waveforms in the archive of that observatory. On average, travel times are 3.9 s earlier than IASP91 times and these residuals have a standard deviation of 2.0 s.

Table 1 shows that the mean *Pn* travel time bias for Soviet PNEs is reduced by 3.2 s. The standard deviation of *Pn* residuals is reduced by a factor of about 2. Kriging residuals to SSSCs provides further

improvement, reducing mean *Pn* travel time bias by up to 3.7 s and the standard deviation of *Pn* residuals by a factor of about 3. We emphasize that these are preliminary results, using Bond r s (1999) method. We shall be obtaining SSSCs by different methods, and we are carrying out a direct evaluation of travel times in 3D structures for the specific purpose of comparing with the more primitive evaluation indicated by equation (1).

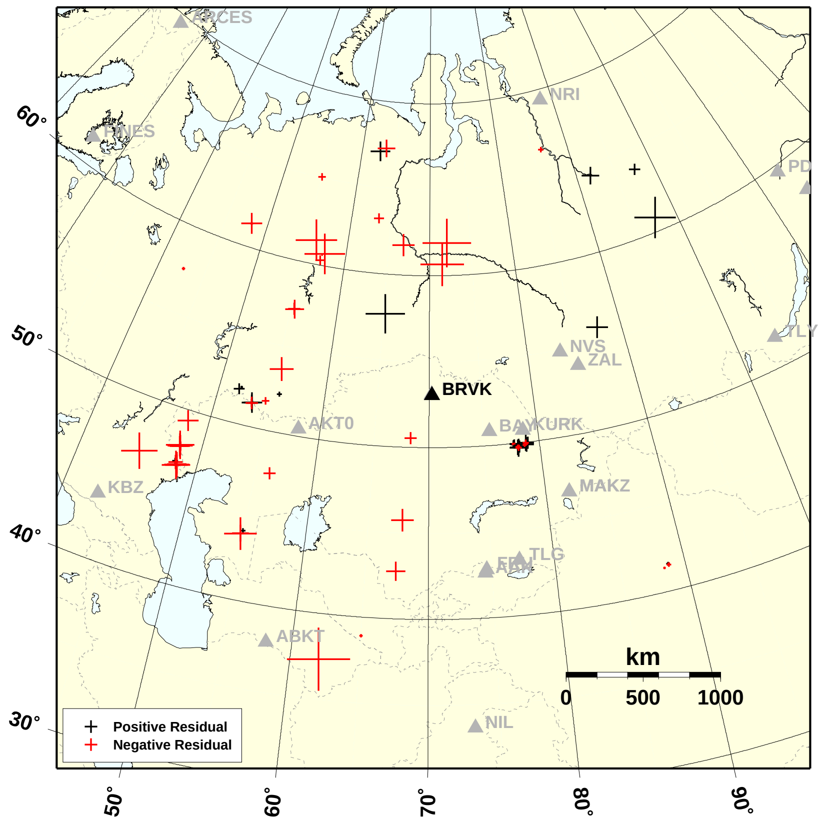


Figure 4. Residuals here are the observed travel time, minus the IASP91 time, minus the SSSC for Borovoye for the appropriate distance and azimuth. On average, observed times are now only 0.4 s earlier that IASP91 times, and have a standard deviation of 1.2 s. Both the average residual and the scatter are significantly improved over Figure 2.

**Table 1. Residuals and variances for Pn travel times at Borovoye, for different source regions**

| Case | IASPEI91 | | SSSC | | SSSC+Kriging | |
|---|---|---|---|---|---|---|
| | $\mu_{\delta T}$ | $\sigma_{\delta T}$ | $\mu_{\delta T}$ | $\sigma_{\delta T}$ | $\mu_{\delta T}$ | $\sigma_{\delta T}$ |
| STS UNE's | +0.50 | 0.44 | +0.11 | 0.42 | +0.05 | 0.32 |
| Lop Nor UNE's | -3.78 | 0.15 | -2.06 | 0.15 | -0.04 | 0.15 |
| Soviet PNE's | -3.91 | 1.96 | -0.67 | 1.29 | -0.40 | 1.16 |
| Overall | -1.68 | 2.57 | -0.36 | 1.07 | -0.15 | 0.83 |

**Validation of our preliminary SSSCs**

The most direct way to demonstrate that a set of SSSCs is useful, is to see if they can provide improved locations when applied to events whose location is in fact known. For the Lop Nor nuclear explosion of 1995 May 15, which occurred during the first year of GSETT-3, we have arrival times of *Pn* at stations NIL, AAK, MAKZ, BRVK, KURK, ZAL, TLY and ULN. Figure 5 shows five different locations for this event, including ground truth (taken from work of Engdahl and Bergman). The location estimate using regional waves interpreted with IASP91 has considerable uncertainty, significantly reduced when SSSCs for these eight stations are applied. The best location is based on regional and teleseismic signals. Table 2 summarizes the improvement in location given by using our preliminary SSSCs for Lop Nor explosions.

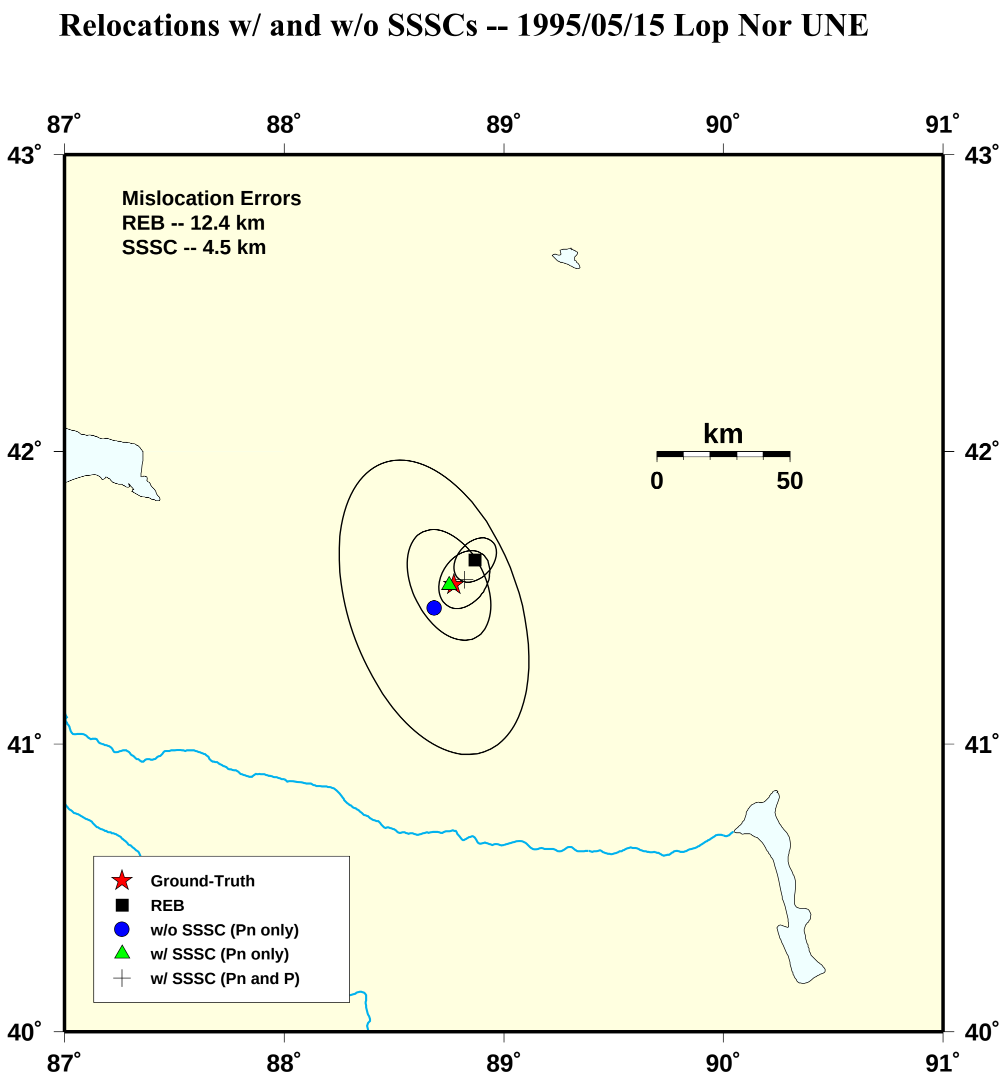


Figure 5. The ground truth location here (red star) is taken from work of Engdahl and Bergman. The REB location (black square) has a small confidence ellipse but it does not include the actual location. A location estimate using regional waves only, interpreted with IASP91 (blue circle) has large uncertainty. The location estimate using regional waves with SSSCs for eight regional IMS stations (green triangle) shows a good result. The location using regional and teleseismic waves gives the best result (black cross).

**Table 2. Location performance metrics for Lop Nor explosions**

| | Pn phases only | | P + Pn phases | |
|---|---|---|---|---|
| | w/o SSSC | w/ SSSC | w/o SSSC | w/ SSSC |
| Mean mislocation error (km) | 112.8 | 19.1 | 12.9 | 7.7 |
| Mean error ellipse size (km$^2$) | 66,389 | 15,282 | 950 | 580 |

**Additional datasets for empirical travel times in Eastern Asia**

The Soviet-era PNEs and underground nuclear explosions (UNTs) at weapons test sites were recorded by hundreds of stations within the territory of the former Soviet Union, that typically did not report those arrival times in the open literature. Arrival times of these events were reported to the International Seismological Centre (ISC) by hundreds of stations in Eastern Asia. And of course many of the PNEs and some of the UNTs were very well recorded by hundreds of temporary field stations deployed in long profiles within the U.S.S.R. In addition to the use of Bond r s (1999) method, we are building a dataset of all these travel times that can be used to obtain SSSCs more directly from observations. The principal work of building this dataset, is resolving hundreds of questions on

¥ what to do when different analysts pick different arrivals from the same waveform, and
¥ what to do when different station coordinates are listed by different organizations for different stations.

This work is well in hand. For example, for phase data collated by Ivan Kitov of the Institute of Dynamics of the Geosphere (IDG) from 83 PNEs and UNTs from Novaya Zemlya (35 tests) and Semipalatinsk Test Site (80 tests), one question is concerned with the 129 Soviet station locations associated with arrival picks in the data and how these should be merged with the reports of the same events given at 915 stations (east of 20E and north of 5N) for which IDG has also collated phase data derived from the ISC bulletin. These data provide dense coverage, as indicated by Figure 6, but to use these data we needed to resolve the following issues:
1) There are duplicate station "codes" but different locations.
2) The station list file has 1044 stations (129 Soviet + 915 derived from ISC) but 944 stations when duplicate code names are removed.
3) In case of phase picks for PNEs, there are 106 stations with more than 20 observations and 236 stations with fewer than 20 picks. We have examined all of these 106 stations and have used numerous contacts with knowledgeable sources of information in the former Soviet Union to decide the best station locations.
4) The ISC station list and the principal Soviet station list contain different station codes for the same station, as well as the same code for different stations, which must all be resolved.
5) Finally, when the station database is constructed, operation start and end time has to be entered in the case of several stations that were moved, and the best information from station operators has to be used.

The outcome of this major effort, is a groomed list of 355 station coordinates in which we have confidence, for stations that reported the vast majority of the phase pick data for Soviet PNEs and UNTs.

Additional to the nuclear explosion phase-pick databases we have listings of tens of thousands of seismic event locations in Kyrgyzstan, Southern Kazakhstan, and the Altay-Sayan and Baykal regions of Russia. We are working to obtain subsets of these events that are GT5 quality, and preferably events that occurred since January 1995 (the beginning of full-time GSETT-3 operations) with magnitude large enough to give

unambiguous picks at the IMS stations were are studying. For events in Tibet and the Indian sub-continent, our consortium partner at URS Greiner, Chandan Saikia, is providing a small number of GT5 events and a much larger set of GT10 events.

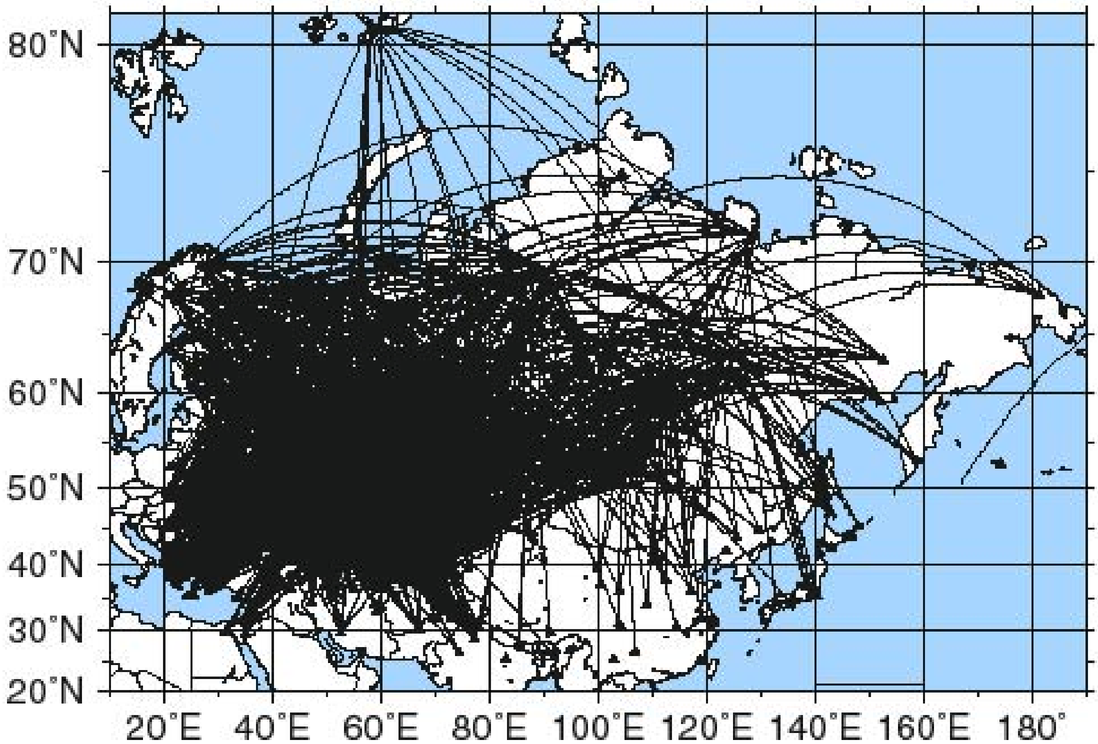


Figure 6. Great circle paths between the PNEs (stars) and stations (triangles) for which phase data are reported from 83 Soviet-era PNEs at standard and regional stations of the former Soviet Union and other stations in Eurasia, as collated by staff of the Institute of Dynamics of the Geosphere (Moscow). We have worked with several sources of information on station operations to resolve numerous questions of the station locations used in this dataset, which is a valuable resource for IMS station location calibration.

**Spatial Clustering of Seismicity in China**

We have begun to collect high-precision hypocenter locations for mainland China by applying a double-difference (DD) earthquake relocation technique (Waldhauser and Ellsworth, 2000) to travel time data listed in the Annual Bulletin of Chinese Earthquakes (ABCE). This dataset is described by Hearn and Ni (2000). The DD technique uses travel time differences between nearby earthquakes recorded at common stations to solve for highly accurate hypocentral separations between the events. It therefore works best in areas with dense earthquake distribution, where it minimizes effects due to unmodeled velocity structure without the use of station corrections. The method is not sensitive to errors of a few km in station location, unless used to locate events at distances of less than a few tens of km, because it is only the travel time difference that is used, and the azimuth of two events not far apart will be almost the same at each station.

We have formed travel time differences from about 140,000 *P*- and *S*-phases of about 6,000 events (magnitudes 2.7 - 7.1) listed in the ABCE for seven different years. Due to the sparse spatial distribution of the events, and thus the somewhat large average distance between hypocenters, small clusters of up to 70 events could be formed only in areas where the seismicity is dense enough. In these areas the average location accuracy improved after relocation by more than an order of magnitude compared to the ABCE locations.

Figure 7 shows the DD results for four examples, of event clusters that occurred in eastern (Cluster 1), southern (Cluster 2 and 3), and western (Cluster 4) China. The top row of panels indicates the location of the clusters and the stations used to relocate the earthquakes. Panels in the second and third row show the epicenters as listed in the ABCE catalog and after DD relocation, respectively. In Cluster 1 to 3, strong spatial clustering is observed which appears to delineate local tectonic features. In Cluster 4 the relocated events are more diffuse, most likely due to the sparse station distribution.

Analysis of the residuals of travel time differences indicate that the phase picks are of high quality, as noted by Hearn and Ni (2000). Thus this data is best suited to image seismicity with high resolution on a local scale where events locate close together. Increasing earthquake density by including ABCE data from additional time periods might help to relocate earthquakes over larger distances, such as entire fault systems. Such studies would have the potential to contribute to a better understanding of the tectonic processes that take place in China as well as to provide groundtruth data for our location calibration work.

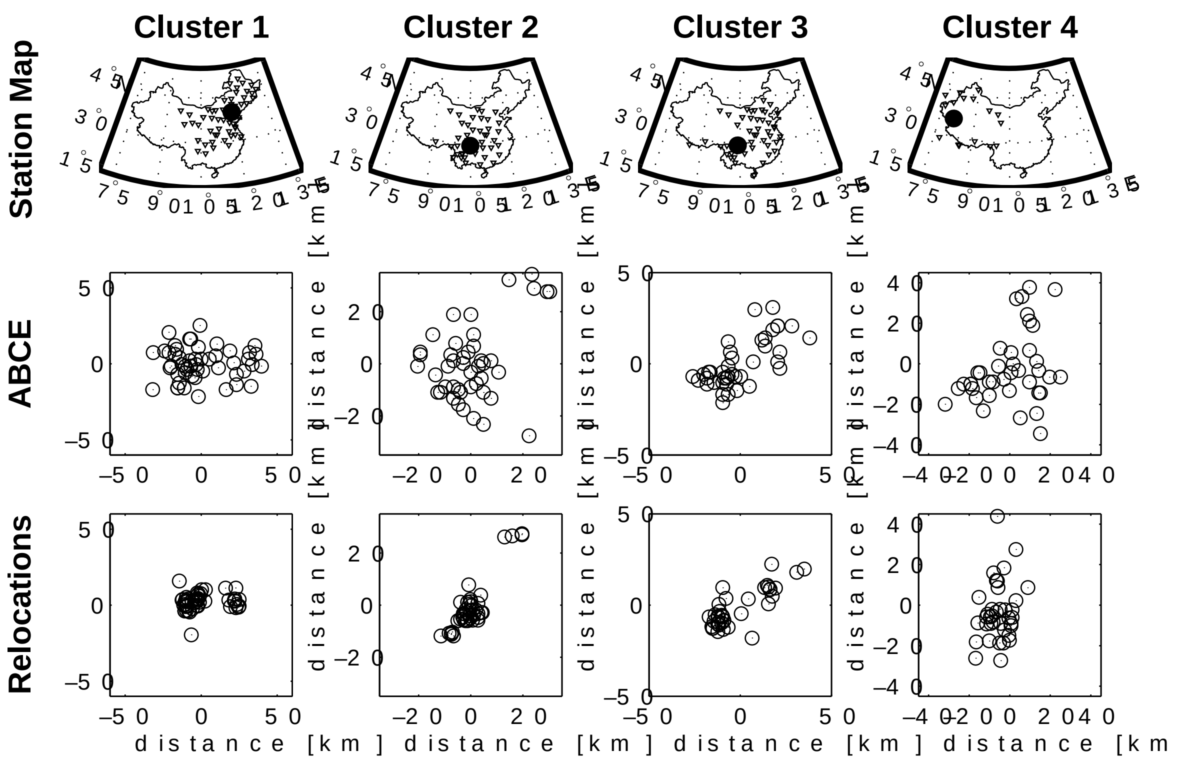


Figure 7. Examples of double-difference locations for four earthquake clusters on mainland China. Top row: location of clusters and stations used in the relocation. Middle row: location of epicenters as listed in the ABCE catalog. Bottom row: location of epicenters after relocating the events with the DD method.

## CONCLUSIONS AND RECOMMENDATIONS

We have obtained preliminary SSSCs for IMS stations in Eastern Asia, that demonstrably improve location estimates in the limited number of cases where we have sought this basic validation.

We recommend the use of empirical datasets of travel times from well-documented (GT5 or better) seismic events, (1) to aid in the evaluation of our preliminary SSSCs, (2) to enable kriging residuals on our preliminary SSSCs, and (3) to permit independent derivations of SSSCs using methods other than that of Bond r (1999) on which we are currently relying. We shall be carrying out these three different uses of empirical data.

Since SSSCs can be produced by several different methods, and by different groups of researchers studying the same set of stations, it will be important to develop procedures that enable different SSSCs to be objectively compared, and ranked as to their effectiveness.

## ACKNOWLEDGEMENTS

We acknowledge the assistance of numerous operators of local and regional networks in Central Asia; also Tom Hearn and Jim Ni for information on Chinese seismicity and how it is reported, Jack Murphy for helpful discussions of Soviet PNE data, and Bob Engdahl for access to Lop Nor datasets (groomed ISC phase picks, and location estimates based on hypocentroidal decomposition).

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